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Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response

Andrew Simon [a,*], Massimo Rinaldi [b]

[a] *USDA — Agricultural Research Service, National Sedimentation Laboratory, P.O. Box 1157, Oxford, MS 38655, USA*
[b] *Dipartimento di Ingeneria di Civile, Universita degli Studi di Firenze, 50121, Firenze, Italy*

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Abstract

Channel incision is part of denudation, drainage-network development, and landscape evolution. Rejuvenation of fluvial networks by channel incision often leads to further network development and an increase in drainage density as gullies migrate into previously non-incised surfaces. Large, anthropogenic disturbances, similar to large or catastrophic "natural" events, greatly compress time scales for incision and related processes by creating enormous imbalances between upstream sediment delivery and available transporting power. Field examples of channel responses to antrhopogenic and "natural" disturbances are presented for fluvial systems in the mid continent and Pacific Northwest, USA, and central Italy. Responses to different types of disturbances are shown to result in similar spatial and temporal trends of incision for vastly different fluvial systems. Similar disturbances are shown to result in varying relative magnitudes of vertical and lateral (widening) processes, and different channel morphologies as a function of the type of boundary sediments comprising the bed and banks. This apparent contradiction is explained through an analysis of temporal adjustments to flow energy, shear stress, and stream power with time. Numerical simulations of sand-bed channels of varying bank resistance and disturbed by reducing the upstream sediment supply by half, show identical adjustments in flow energy and the rate of energy dissipation. The processes that dominate adjustment and the ultimate stable geometries, however, are vastly different, depending on the cohesion of the channel banks and the supply of hydraulically-controlled sediment (sand) provided by bank erosion.

The non-linear asymptotic nature of fluvial adjustment to incision caused by channelization or other causes is borne out in similar temporal trends of sediment loads from disturbed systems. The sediments emanating from incised channels can represent a large proportion of the total sediment yield from a landscape, with erosion from the channel banks generally the dominant source. Disturbances that effect available force, stream power or flow energy, or change erosional resistance such that an excess of flow energy occurs can result in incision. Channel incision, therefore, can be considered a quintessential feature of dis-equilibrated fluvial systems.
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1. Introduction

The causes of river channel incision are numerous, but the morphological effects and hazards associated

* Corresponding author.
E-mail address: asimon@ars.usda.gov (A. Simon).

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with incised channels are often similar, across a spectrum of physiographic environments (Parker and Andres, 1976; Elliott, 1979; Schumm et al., 1984; Williams and Wolman, 1984; Simon, 1989a, 1992; Rinaldi and Simon, 1998; Schumm, 1999). Incision is a common response of alluvial channels that have been disturbed such that they contain excess amounts of flow energy or stream power relative to the sediment load. Channel incision, however, represents only one response among a range of possible adjustment scenarios for disturbed streams that are free to adjust boundaries. The purposes of this paper, therefore, are threefold: (1) to present findings on the nature of channel incision and related processes in disturbed alluvial systems, (2) to examine some of the drivers of stream incision, with a particular focus on channelization, one of the most widespread human activities that drives incision; and (3) to place incision in the broader general context of the driving and resisting forces that govern channel adjustment. This is accomplished by analyzing channel adjustment in terms of the imbalance between flow energy or stream power and sediment load, and by using field-based studies and numerical-modeling examples of unstable channels.

Incised channels range in size from small, alluvial rills at the scale of centimeters to bedrock canyons at the

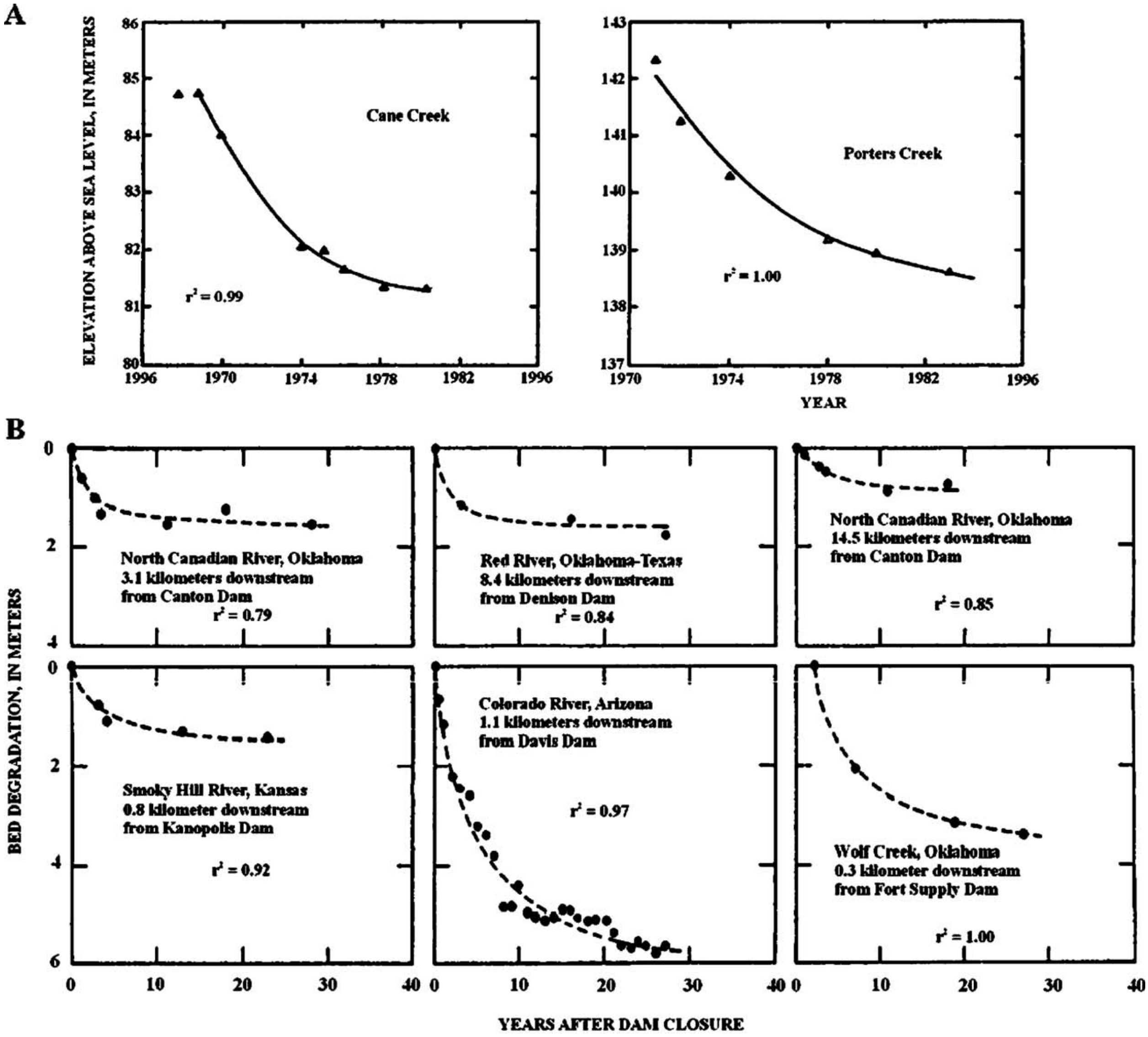

Fig. 1. Typical non-linear trends of bed-level adjustment after channelization in West Tennessee (modified from Simon, 1989a) (A), and downstream of dams in the mid-continent USA (modified from Williams and Wolman, 1984) (B).

scale of kilometers. Whatever the scale, the defining characteristic of incised channels is that they can contain flows of greater recurrence intervals than non-incised channels in similar hydrologic settings. Thus, at some point in history, these channels have undergone progressive bed-level lowering (degradation), although overbank deposition and construction of levees can lead to similarly "deepened" channels. Because an incised channel can contain larger peak flows and often cannot dissipate flow energy across the former floodplain, these channels are particularly dynamic.

Causes of channel incision have been grouped into six major categories by Schumm (1999): geologic, geomorphologic, climatic, hydrologic, animals, and humans, with specific mechanisms associated with each cause. Yet in terms of process and response, all of the major causes of channel incision can be linked to excess sediment-transporting capacity relative to the quantity of bed-material sediment delivered from upstream reaches.

Degradation of channel beds represents a response to a disturbance in which an excess of flow energy, shear stress or stream power (sediment-transporting capacity) occurs relative to the amount of sediment supplied to the stream. This is often expressed using the stream power proportionality popularized by Lane (1955) which is applicable to channel with mobile boundaries:

$$QS \propto Q_s d_{50} \tag{1}$$

where Q is the channel-forming discharge (m^3 s^{-1}), S is the channel gradient, Q_s is the bed-material discharge (m^2 s^{-1}), and d_{50} is the median grain size of the bed material (m). Degradation differs from the localized bed-erosion process termed "scour," which is generally limited in magnitude as well as in spatial and temporal extent. Scour can occur over periods of hours to days and affects localized areas in response to stormflow. In contrast, the process of degradation, which represents systematic bed-level lowering over a period of years (Mackin, 1948), can affect long stream reaches, entire lengths of one stream, or whole stream networks.

2. Temporal and spatial trends of incision

By relation 1, degradation will occur if changes imposed on an alluvial channel, be they "natural" or anthropogenic, cause a decrease in sediment loads, an increase in annual or peak discharges, concentration of flow, or an increase in channel gradient. The degradation process will migrate downstream in the case of bed-level adjustment below a dam, and upstream in the case of a disturbance such as bed-material mining or channelization (Fig. 1). The process can migrate as a series of knickpoints if the material is cohesive and resistant, or in sand-bed streams as a broader, locally steeper section called a "knickzone". Fig. 2 shows the upstream migration of the degradation process from time-series data of low-flow water-surface elevations for several sites along the South Fork Forked Deer River, West Tennessee. Here, initial channel enlargement and straightening from the mouth to near Yellow Bluff in 1967 and 1968 caused incision upstream to the gage near Halls by 1970, and to Gates, 21.4 km upstream of the channel work, by the mid 1970s.

Using the coefficient (a) of an exponential decay function to describe the non-linear rate of bed-level change with time, the attenuation of the degradation process with distance can be identified and quantified (Simon, 1992):

$$z/z_o = a + (1-a)e^{(-kt)} \tag{2}$$

where z is the elevation of the channel bed at time t; z_o is the elevation of the channel bed at $t_o = 0$; a is a dimensionless coefficient, determined by regression and equal to the dimensionless elevation (z/z_o) when Eq. (1) becomes asymptotic; $1-a$ is the total change in the dimensionless elevation (z/z_o) when Eq. (1) becomes asymptotic; k is a coefficient determined by regression that indicates the rate of change on the channel bed per unit time; and t is the time (years) since the onset of the adjustment process. When $a>1$, aggradation is occurring; when $a<1$, degradation occurs. Likewise,

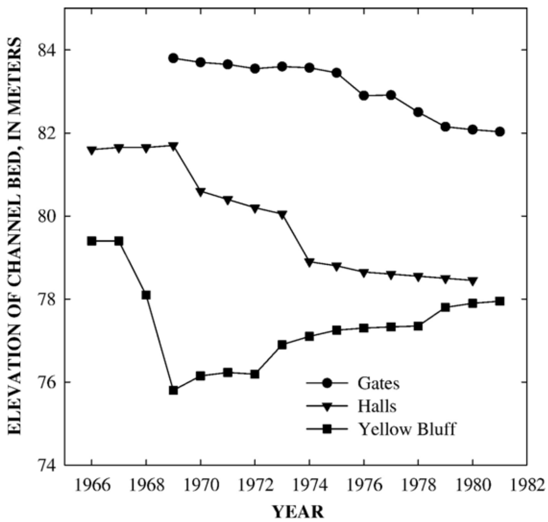

Fig. 2. Example from the South Fork Forked Deer River, West Tennessee illustrating the upstream migration of degradation with time. Note: Yellow Bluff is the farthest downstream, Gates the farthest upstream (modified from Robbins and Simon, 1983).

when $(1-a)>0$ then degradation is occurring, but when $(1-a)<0$, then aggradation occurs.

An example from the Obion River System is shown in Fig. 3A, where maximum degradation rates (smallest a values) occur at the upstream end of the channel work, representing the area of maximum disturbance, and attenuate with distance upstream. Each data point ($a<1$) shown in this figure represents degradation trends of the kind shown in Fig. 1A. Downstream from this area the channel is unable to transport all of the sediment being delivered from degrading reaches and tributaries upstream resulting in aggradation ($a>1$). This empirical model of bed-level adjustment is not unique to this coastal plain setting or to a system disturbed by anthropogenic means. The North Fork Toutle River, Washington was buried by a massive debris avalanche following the primary 1980 eruption of Mount St. Helens. In this case, an increase in potential energy provided by ~60 m of deposition along the middle reaches of the river caused 20–30 m of degradation in some reaches (Simon, 1999). Trends of bed-level adjustment to this form of excess energy are strikingly similar to those of the Obion Forked Deer River System (Fig. 3B), with maximum degradation occurring at the area of maximum disturbance, with attenuating degradation upstream and aggradation downstream.

Channel incision results in higher and often steeper streambanks. If sufficient downcutting occurs, streambanks can become susceptible to mass failure resulting in channel widening. Reaches of unstable banks can supply enormous quantities of sediment to the flow, potentially damping rates and magnitudes of degradation depending on whether the bank sediments are coarse-or fine-grained (Simon and Darby, 1997). Sediment derived from streambank failures can be the dominant source of sediment in a watershed containing incised channels (Table 1).

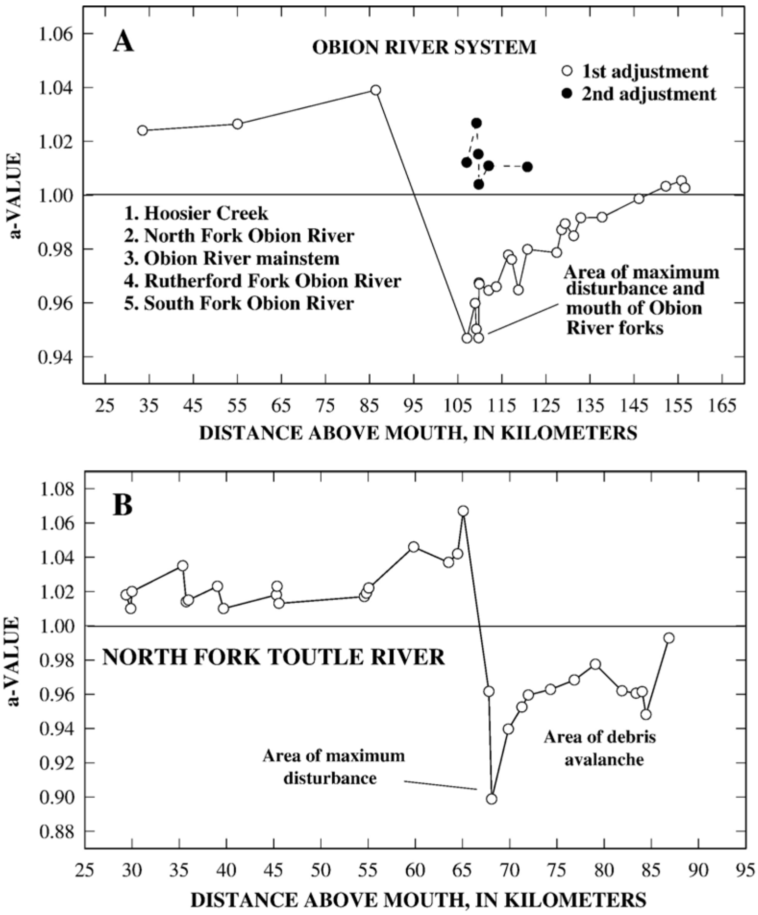

Fig. 3. Strikingly similar empirical models of bed-level adjustment for the Obion River System, West Tennessee (A) and the North Fork Toutle River, Washington (B) showing attenuation of incision with distance above the area of maximum disturbance and aggradation downstream (from Simon, 1992).

Table 1
Contributions of streambank erosion to total sediment load in incised channels in the southeastern United States

Stream	Ecoregion	Bed material	Contribution from banks
James Creek, MS[1]	Southeastern Plains	Sand/clay	78%
Shades Creek, AL[2]	Ridge and Valley	Gravel	71–82%
Goodwin Creek, MS[3]	Mississippi Valley Loess Plains	Sand/gravel	64%
Yalobusha River, MS[4]	Southeastern Plains	Clay/sand	90%*
Obion Forked Deer[5] River, TN	Mississippi Valley Loess Plains	Sand	81%*

Note: Values marked with an * indicate the contribution from banks relative to all channel sources. [1] from Simon et al. (2002), [2] from Simon et al. (2004a), [3] from E. Langendoen, USDA-ARS, per. commun. (2006), [4] from Simon and Thomas (2002), 5 from Simon and Hupp (1992).

Using the Obion River System, West Tennessee and the Toutle River System Washington as examples again, average rates of widening during adjustment differ by more than an order of magnitude; about 0.5–1.0 m/y, and 10–20 m/y, respectively (Fig. 4). The reason for this difference is the varying resistance of the bank materials to failure by gravity. Whereas banks of the Toutle River System are composed of non-cohesive materials, banks of the Obion River System are silt-clay and possess cohesive strength to resist mass failure. Still, as will be seen later, channel widening is a critically important adjustment process in incised streams.

The time rate of energy dissipation per unit channel length can be defined in terms of total stream power per unit channel length (Leopold et al., 1964):

$$\Omega = \gamma w y v S = \gamma Q S \tag{3}$$

where Ω is the total stream power per unit length (N/s); γ is the specific weight of water (N/m^3); w is the water-surface width (m); y is the hydraulic depth (m); v mean flow velocity (m/s); and S is the energy slope (m/m).

Thus, channel adjustment, indicated by an imbalance in Eq. (1), represents adjustment of dissipation energy Eqs. (2) and (3); an increase in stream power by

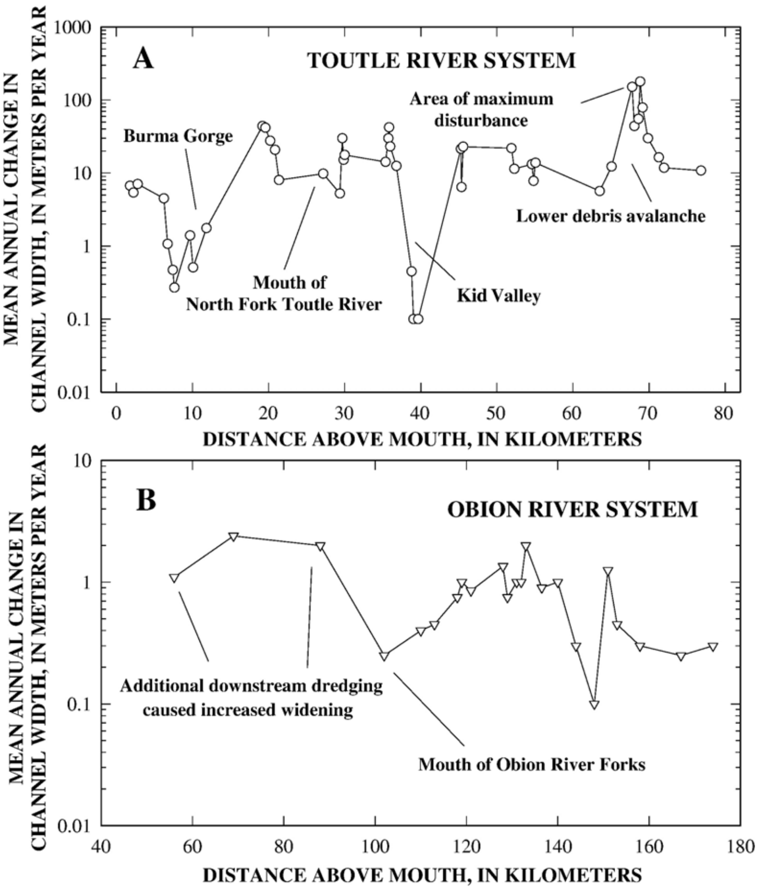

Fig. 4. Annual rates of channel widening for the Toutle River System (A), and the Obion River System (B) following disturbance (from Simon, 1992).

disturbance is offset by processes that will decrease stream power and energy dissipation. Still, understanding the hierarchy of channel adjustment processes and resulting forms can be better appreciated using equations for total-mechanical energy which explicitly characterize the interdependence between hydraulic processes, channel geometry, and flow resistance (all of which can change with time).

Identifying in-stream sediment sources, dominant processes of adjustment, and morphologic change becomes a matter of determining the relative resistance of the bed and bank material to the applied forces imposed by the flow and/or by gravity. For a sand-bed stream with cohesive banks, an initial adjustment might involve streambed incision because of low critical shear stresses, higher applied shear stresses on the bed than on the bank-toe, and more frequent exposure to hydraulic shear than adjacent streambanks. Conversely, if we assume that the streambed is highly resistant, composed of cohesive clays, bedrock, or large clasts such as cobbles or boulders, and that the bank-toe is composed of significantly weaker materials, we could expect bank erosion to be the initial adjustment as a means of minimizing the imbalance between stream power and sediment transport.

3. Channelization

The practice of channelization can represent a direct, drastic form of anthropogenic disturbance to a fluvial system. Channelization is an engineering practice that involves the physical re-alignment of a channel, often with removal of meanders (Fig. 5) to create a straight channel for purposes of (Brookes, 1988): 1) reducing flood magnitude and frequency, 2) improving navigation, 3) controlling bank erosion, and 4) relocating for infrastructure construction.

Evidence of the practice of channelization dates back thousands of years to ancient Egypt where water from the Nile River was diverted for irrigation. Construction of embankments and drainage ditches took place on the Yellow River in China around 600 BC and in Tuscany, Italy and Britain 2000 years ago during Roman rule (Brookes, 1988; Billi et al., 1997). In lowland countries of Western Europe such as Denmark, The Netherlands and northern Belgium, channelization has been widespread. In Denmark, almost 98% of the country's watercourses have been straightened (Brookes, 1987).

The practice of channelization often involves lowering the streambed by dredging, and generally increasing channel capacity. Dredging and straightening significantly increase channel capacity and gradient, resulting in a proportionate (possibly exponential) increase in bed-material discharge, resulting in rapid morphologic changes over distances that can include entire fluvial systems (Eq. (1)). These changes include upstream degradation, downstream aggradation (in sand-bedded streams), and bank instabilities along altered streams and adjacent tributaries. Some channelized streams, however, particularly those in low-relief environments with resistant boundary materials, do not conform with the sequence of channel adjustments typical of alluvial systems where degradation is followed by widening and then filling (Landwehr and Rhoads, 1993). Instead of an erosional response to channelization, such channels typically undergo an aggradational response, followed by stabilization because of insufficient transport capacity relative to heightened loadings. Barnard and Melhorn (1982) describe increases in sinuosity (gradient reduction) in response to channelization. These alternative responses can readily be explained on the basis of a process-based understanding of the fluvial dynamics of modified streams in these types of environments.

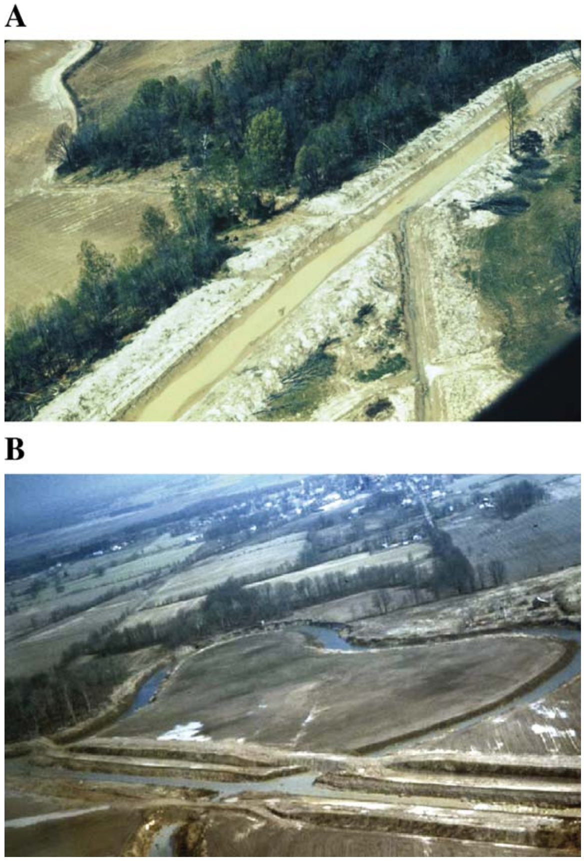

Fig. 5. Examples of channelization of a fluvial network (A) and, meander removal (B).

Widening of the channel bed during channelization results in a decrease in stream power per unit area during transport-effective flows, which in turn leads to deposition until the inset channel formed by this deposition has enough power to transport the supplied sediment (Rhoads, 1990). A similar scenario occurs in downstream reaches of channelized streams where the massive increase in sediment loads delivered to these reaches cannot be transported by the range of flows, resulting in deposition as the typical response. Reaches such as these often display braided-channel configurations.

4. Channelization programs in the mid-continent, USA

Programs of channelization in the United States date back about 150 years and are related to the effects of intensive agricultural activities following settlement of the region. Large tracts of land were cleared for cultivation prior to and after the American Civil War (Ashley, 1910; Brice, 1966; Piest et al., 1977). Stream courses were tortuous with sinuosities ranging from about 3 to 4, with valley slopes in the order of 10^{-4} to 10^{-3} m/m (Moore, 1917; Speer et al., 1965). Channels were often characterized by accumulations of large wood and beaver dams. Channel gradients from trunk streams in southeastern Nebraska and West Tennessee were about 1.2 and 1.1×10^{-4} m/m, respectively (U.S. Army Corps of Engineers, 1907; Moore, 1917). The removal of grasses and woody vegetation from watersheds for cultivation resulted in reduced water interception and storage, increased rates of surface runoff, erosion of uplands, and gullying of flood plains and terraces. Rates of surface runoff and peak-flows in western Iowa are estimated to have increased 2–3 times and 10–50 times, respectively, when compared to estimates of pre-settlement amounts (Piest et al., 1976; 1977). The removal of woody vegetation from streambanks resulted in decreased hydraulic roughness, increased flow velocities and stream power, and contributed to increased peak discharges. In combination, these factors caused extensive downcutting (Piest et al., 1976). Much eroded material was deposited in channels resulting in a loss of channel capacity and frequent and prolonged flooding of agricultural lands (Morgan and McCrory, 1910; Moore, 1917; Piest et al., 1976). Moore (1917) reports that aggradation was almost continuous along the trunk streams of southeastern Nebraska.

As a result of ubiquitous channel filling, local drainage districts implemented programs to dredge, straighten, and shorten stream channels (channelize) to reduce flooding and, thereby, increase agricultural productivity (Hidinger and Morgan, 1912; Moore, 1917). Work was undertaken in southeastern Nebraska, Mississippi, West Tennessee and west-central Illinois around 1910 (Moore, 1917, Speer et al., 1965); around 1920 in western Iowa (Lohnes et al., 1980). In many areas, this work increased channel gradients by about an order of magnitude (Moore, 1917; Simon, 1994). Entire lengths of trunk streams were channelized in southeastern Nebraska and in West Tennessee. By the 1930s most streams tributary to the Missouri and Mississippi Rivers in the loess area of the midwestern United States had been dredged and straightened (Fig. 6; Speer et al.,

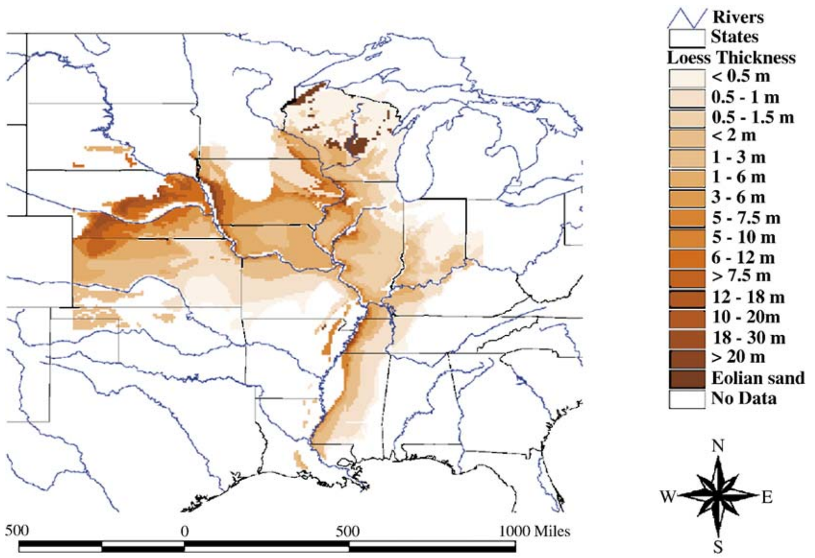

Fig. 6. Thickness of loess deposits in the mid-continent of the United States (modified from Luttenegger, 1987).

1965; Piest et al., 1976; Lohnes et al., 1980; Simon, 1994). In many parts of the region these activities were conducted periodically throughout the 1960s and 1970s as additional tributaries were channelized and because some previously dredged channels filled with eroded sediment from upstream reaches (Lohnes et al., 1980; Simon, 1994).

4.1. Effects of channelization in the mid-continent, USA: excess flow energy

In parts of the loess area of the midwestern United States, channel degradation in response to channelization has resulted in a fourfold increase in channel depth (6 m) and an almost fivefold increase in channel width (about 30 m) since the middle of the 19th century (Piest et al., 1976; 1977). Erosion rates from two severely degraded silt-bed streams in western Iowa were calculated at 131,000 and 145,000 tonnes/year (T/y) (Ruhe and Daniels, 1965; Piest et al., 1976). In the 20 years of channel adjustment following modification of about 150 km of channels in the Obion River System, West Tennessee, an estimated 6.3 million m^3 of channel sediments were eroded and transported out of the system (11 million T/y; Simon, 1989b). About 1.7 million T/y were discharged from the Obion-Forked Deer Basin, West Tennessee, between the early 1970's and 1987. Expressed in terms of sediment yield (in $T/y/km^2$; Table 2)) sediment production from these systems are 1–2 orders of magnitude greater than those reported by Simon et al. (2004b) for stable systems in the region. On average, about 19% of this material was eroded from the channel bed, the remainder came from the channel banks (Simon, 1989b). The average rate of knickpoint migration and, therefore, rejuvenation of Willow Creek, western Iowa, was about 0.8 km/y (Daniels, 1960), and about 2.4 km/y for the Obion-Forked Deer River System, West Tennessee, (Simon and Hupp, 1992). In West Tennessee, as much as 6 m of degradation and 5 m/y of channel widening have occurred. In Mississippi, Wilson, 1979 reported maximum streambed degradation of about 7 m.

Table 2
Reported rates of erosion from channelized streams in the mid-continent of the United States

River	State	Erosion rate ($T/y/km^2$)	Reference
Obion-Forked Deer River	Tennessee	770	Simon (1989b)
Hotophia Creek	Mississippi	2300	Little and Murphey (1981)
Willow Creek	Iowa	400	Ruhe and Daniels (1965)
West Tarkio Creek	Iowa-Missouri	410	Piest et al. (1976)
Yalobusha River	Mississippi	989	Simon and Thomas (2002)

4.2. Responses: channel evolution in the mid-continent, USA

Alluvial channels destabilized by different “natural” and anthropogenic disturbances can systematically pass through a sequence of channel forms with time (Davis, 1902; Ireland et al., 1939; Schumm and Hadley, 1957; Daniels, 1960; Emerson, 1971; Keller, 1972; Elliott, 1979; Schumm et al., 1984; Simon and Hupp, 1986; Simon, 1989b). The continuum of channel change can be conceptually segmented into discrete phases or stages, each characterized by the dominance of particular adjustment processes. These temporally-and spatially organized adjustments are collectively termed “channel evolution” and permit reconnaissance-level interpretation of past, present, and future channel processes. The basis for these schemes is that evolution is often triggered when an excess supply of stream power or flow energy occurs relative to the load of hydraulically-controlled sediment (sands and gravels) delivered from upstream. Shifts in stages of channel evolution represent the crossing of specific geomorphic thresholds and the dominance of processes associated with those thresholds.

Using the Simon and Hupp (1986) channel-evolution model (Fig. 7), one can consider the equilibrium channel as the initial, predisturbed stage (I), and the disrupted channel as an instantaneous condition (stage II). Rapid channel degradation of the channel bed ensues as the channel begins to adjust (stage III). Degradation flattens channel gradients and consequently reduces the available stream power for given discharges with time. Concurrently, bank heights are increased and bank angles are often steepened by fluvial undercutting and by pore-pressure induced bank failures near the base of the bank. The degradation stage (III) is directly related to destabilization of the channel banks and leads to channel widening by mass-wasting processes (stage IV) once bank heights and angles exceed conditions of critical shear-strength of the bank material. The aggradation stage (V) becomes the dominant trend in previously degraded downstream sites as degradation migrates further upstream because the flatter gradient at the degraded site cannot transport the increased sediment loads emanating from degrading reaches upstream. This secondary aggradation occurs at rates roughly 60% less than the associated degradation rate (Simon, 1992).

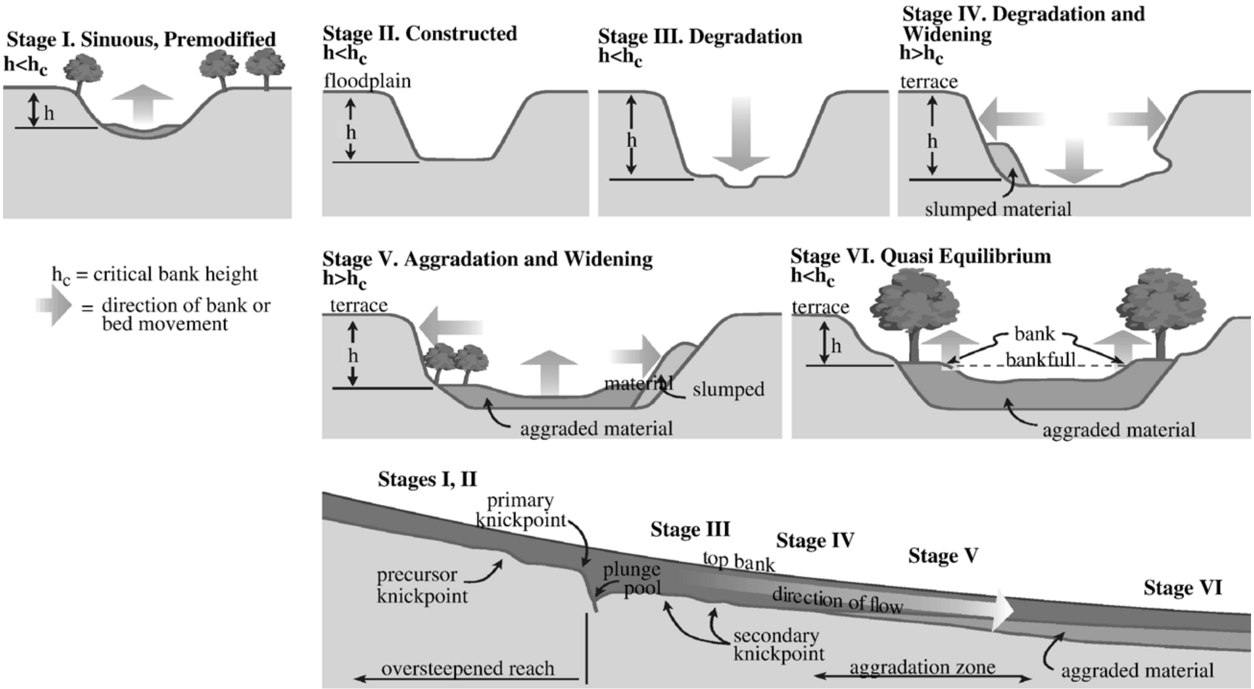

Fig. 7. Stages of channel evolution (modified from Simon and Hupp, 1986).

Riparian vegetation becomes established on low-bank surfaces during this stage and serves as a positive feedback mechanism by providing roughness that enhances further deposition. These milder aggradation rates indicate that recovery of the bed will not be complete and that attainment of a new dynamic equilibrium (stage VI) will take place through further (1) bank widening and the consequent flattening of bank slopes, (2) the establishment and proliferation of riparian vegetation that adds roughness elements, enhances bank accretion, and reduces the stream power for given discharges, and (3) further gradient reduction by meander extension and elongation. The lack of complete recovery of the bed results in a two-tiered channel configuration with the original flood-plain surface becoming a terrace. Stormflows are, therefore, constrained within this enlarged channel below the terrace level and result in a given flow having greater erosive power than when flood flows could dissipate energy by spreading across the flood plain.

Vertical adjustments, such as upstream degradation and downstream aggradation, represent the reduction in channel gradients with time. In some environments, further gradient reduction takes place by increases in stream length and sinuosity. Thorne (1999) describes "late-stage morphologic evolution" through development of cross-section asymmetry in north-central Mississippi as stage VII in the Simon and Hupp (1986) model. The authors have observed this phenomenon in streams that develop sinuosity through adjustment and also in many sinuous streams in the mid-continent of the United States where excessive sediment is vertically and laterally accreted on point bars, deflecting flows downvalley to the opposite bank. Fluvial erosion undercuts the bank leading to failure and a downvalley extension and progression of these meanders.

This sequence of adjustments is common in many areas of the mid continent and elsewhere but is not meant to insinuate that every reach impacted by channelization will undergo these stages (processes and forms) in sequence. As will be shown below, they are typical throughout areas of at least moderate relief. Still, it is not uncommon in these systems for downstream reaches to be overwhelmed by the increased sediment loads emanating from incising upstream reaches and to be aggradational from the onset of adjustment. Similarly, increases in sinuosity brought on by excess sediment relative to transport capacity can occur as point bars preferentially grow by vertical and lateral accretion (Barnard and Melhorn, 1982; Pollen et al., 2006). This process tends to migrate downvalley as higher and higher flows are deflected to the opposite side of the channel causing undercutting, streambank collapse and increases in sinuosity. Aggradational responses such as these appear more common in low-gradient systems

(Landwehr and Rhoads, 1993) and in the mid continent, particularly that have been effected by Wisconsian glaciation (B. Rhoads, 2006, written commun.)

In western Iowa, stage of channel evolution was identified by Hadish (1994) from 1993 and 1994 aerial reconnaissance of about 2500 km of streams using the Simon and Hupp (1986) model. Results show that, 56% of the stream lengths were classified as stage IV (widening and mild degradation; Fig. 8). Bed-level recovery (stage V; aggradation and widening) is occurring along about 24% of the stream lengths, predominantly along the downstream-most reaches. This indicates that channel widening by mass-wasting processes was the dominant adjustment process in the degraded streams of western Iowa, occurring along about 80% of the observed stream reaches. Only 6% of the stream reaches were classified as being stable, either premodified (stage I) or restabilized (stage VI) (Hadish, 1994), indicating that about 94% of the stream lengths in western Iowa were considered unstable, adjusting to 20th century channelization activities.

Stage V conditions (aggradation and mass failures) appeared to dominate much of the main stems of the easterly-flowing sand-bedded streams in southeastern Nebraska. Because stage IV conditions (mass failures with bed degradation) were common along tributary streams, channel widening by mass failures, however, was the overall dominant adjustment process in southeastern Nebraska. A reconnaissance-level study conducted by the U.S. Army Corps of Engineers in 1995 using the Simon and Hupp (1986) model estimated the percentage of stream reaches experiencing mass failures at 75%. In contrast to western Iowa where stage III degrading conditions were found in the upstream reaches of most tributary streams, in southeast Nebraska only small upstream tributaries near basin divides were classified as stage III.

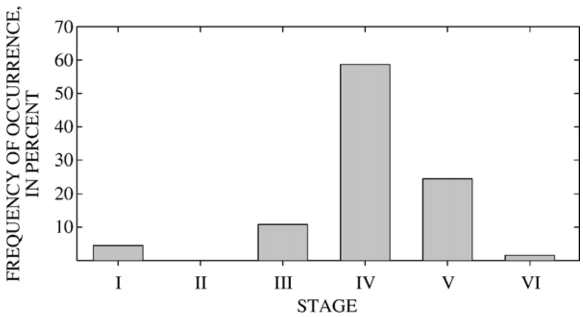

Fig. 8. Distribution of stages of channel evolution (Simon and Hupp, 1986) along 2500 km of streams in western Iowa during 1993 and 1994. Only a very small percentage (stages I and VI) are stable and non-incised. Data from Hadish (1994).

In West Tennessee, about 65% of the 1645 studied sites were unstable, with channel widening occurring at about 60% of them (Bryan et al., 1995). In this part of the loess area, similar comparisons could be made between channel evolution in streams with silt beds (that dominate western Iowa) and those with sand beds (that dominate southeastern Nebraska). Tributaries of the largest, modified West Tennessee streams rise in unconsolidated sand-bearing formations that supply sand to the channels as bed material. Aggradation in downstream reaches occurred after 10–15 years of incision and channel widening occurred at moderate rates (Simon, 1989a). In contrast, smaller tributary streams near the Mississippi River bluff have cut only into loess materials, have silty beds, and no source of coarse-grained material. To reduce erosional forces and stream power for a given discharge without a coarse-grained sediment supply for downstream aggradation, channel widening (stage IV) was the only mechanism for the silt-bed streams to recover (Simon, 1994). The silt-bed channels were the deepest and most rapidly-widening channels in West Tennessee and may take hundreds of years to recover. This was similar to the western Iowa silt-bed streams, such as West Tarkio Creek, where downcutting (stages III and IV) had lasted for as much as 70 years and channel widening was widespread.

5. Case studies: incision by channelization and reduced sediment supply

Two case studies are presented that highlight how similar processes can result from diverse and almost opposite disturbances. Data for West Tarkio Creek, Iowa and Missouri, USA are presented as a typical scenario following increased flow energy because of channelization. In contrast, similar channel changes on the Arno River, Italy are shown to be the result of reduced sediment supply.

5.1. West Tarkio Creek, Iowa and Missouri, USA

West Tarkio Creek incised in the middle 1800s as a result of increased rates of runoff emanating from cleared lands (Piest et al., 1977) and has been undergoing renewed channel adjustment since being straightened in about 1920. The channel displays the systematic variation in stage of channel evolution with distance upstream as shown in Fig. 7; aggradation (stage V) in its downstream-most reaches merging to widening with mild degradation (stage IV) in middle reaches, to rapid degradation (stage III) in the upstream reaches (Fig. 9). The dominant class of bed material generally

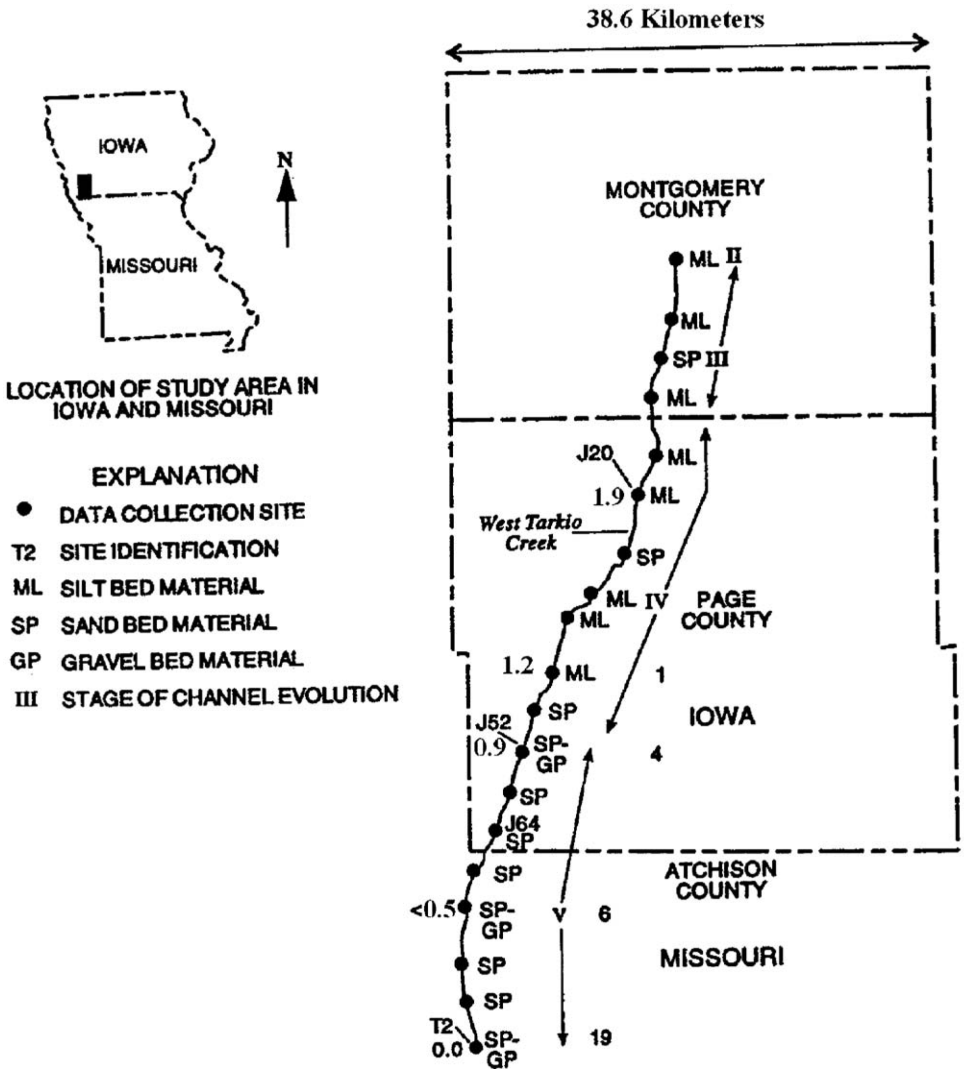

Fig. 9. Map of West Tarkio Creek showing stages of channel evolution, dominant bed-material size class, age of oldest riparian tree (years, numbers on right) and widening rate (m/y, numbers on left). Note systematic trends of stage of channel evolution, rates of widening and age of oldest riparian species with distance upstream (from Simon and Rinaldi, 2000).

varies systematically with the stage of channel evolution and distance upstream, with sand beds in aggrading reaches and silt beds in degrading reaches. Piest et al. (1977) describe stable reaches of West Tarkio Creek in 1975 near its junction with the Tarkio River, implying that degradation lasted for about 55 years. By 1994, aggrading conditions on West Tarkio Creek extended at least 8 km into Iowa to the J52 bridge (Fig. 9). Assuming that stable conditions in 1975 were at the confluence with the Tarkio River and were about 25 km further upstream in 1994 than in 1975 (19 years), the average rate of upstream migration of incision was 1.3 km/yr.

Trends of bed-level changes from 1920 to present were obtained by fitting historical data to Eq. (2) (Simon, 1992). Degradation trends at 9 sites are shown in Fig. 10A. The 3 plots in the bottom row of Fig. 10A show that degradation along the downstream-most 18 km of channel was virtually complete by 1980. Degradation continuing beyond the year 2000 was expected along reaches farther upstream until the curves become asymptotic (Fig. 10A). An empirical model of the adjustment of bed-level for West Tarkio Creek is obtained by plotting the a-value coefficient (from Eq. (2)) against distance from the junction with Tarkio River (Fig. 10B).

Changes in channel width were dramatic on West Tarkio Creek. Fig. 10C shows increases in channel width for the period 1845–1994 at a site approximately 3.2 km south of the Iowa–Missouri stateline where the

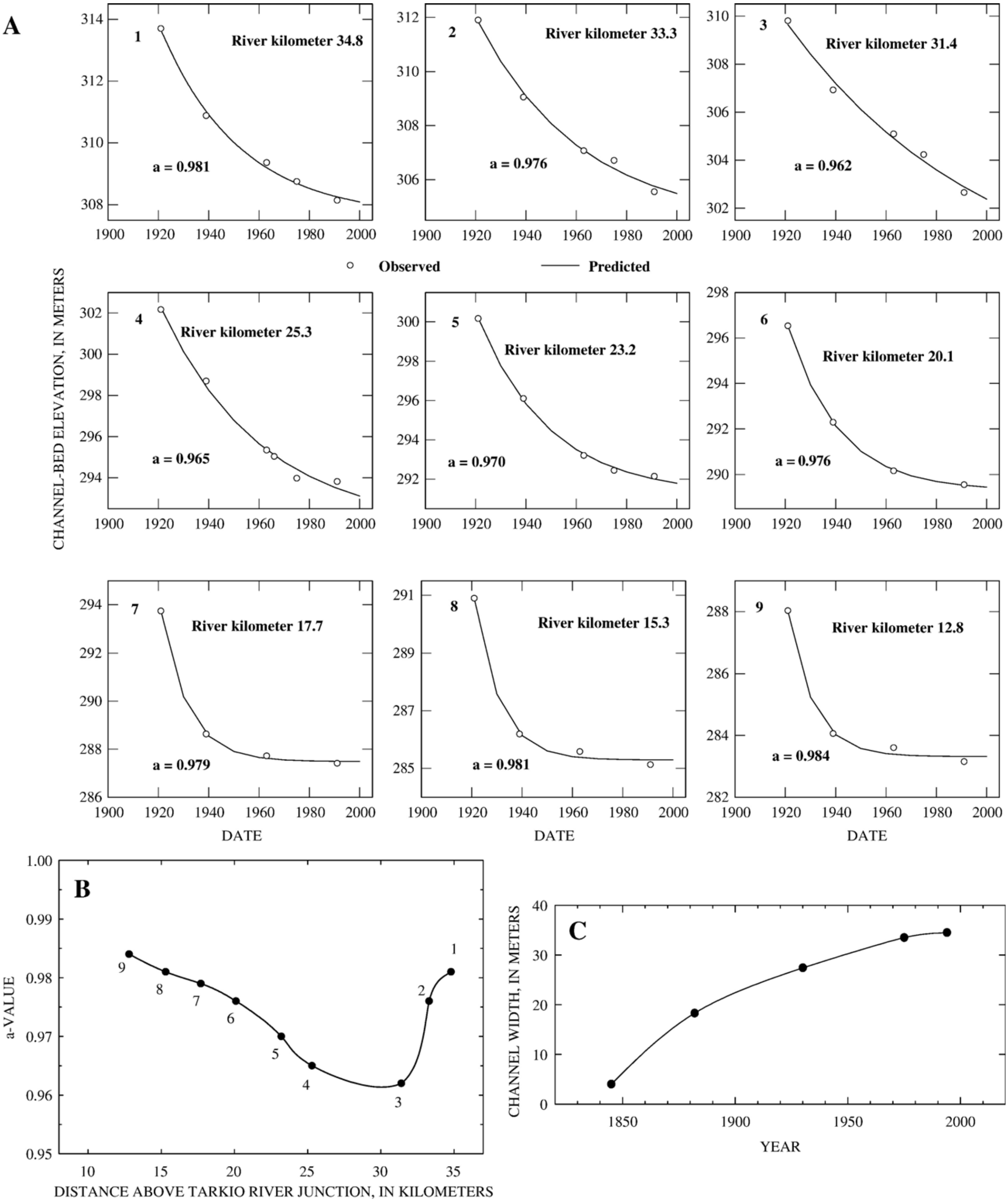

Fig. 10. Trends of degradation for nine sites on West Tarkio Creek fit with Eq. (2) (A) and (B), and changes in top-bank width from 1845–1994 about 3.2 km south of the Iowa–Missouri border (C) (from Simon and Rinaldi, 2000).

recovery of bed-level had started. The asymptotic nature of the plot is typical of recovering reaches where reductions in rates of widening occur as bank slopes are flattened through continued failures, aggradation on the channel bed reduces bank heights, and bank-toe scour is reduced as failed debris becomes colonized with woody vegetation. Williams and Wolman (1984) and Wilson and Turnipseed (1994) used non-linear functions to describe widening trends such as the one shown in Fig. 10C.

5.2. Regional summary: mid-continent, USA

Although sequences of channel evolution are similar throughout the region, distinct differences in the amount of time required for streams to pass from one channel-evolution stage to the next, to exhibit signs of recovery (establishing woody-riparian vegetation, stabilizing streambanks, and a meandering low-flow thalweg), and to attain a new equilibrium condition vary with the sediment composition of the channel boundary. For example, the degradation stage (III) accounts for 10–15 years in the sand-bedded streams of West Tennessee, but about 70 years is needed to reach this stage in the silt-bedded streams of western Iowa. Variations also occur as a result of extremes in precipitation and discharge. Fig. 11 is an idealized representation of relative changes in bed elevation and channel width with the associated stage of channel evolution for mid-continent streams composed of

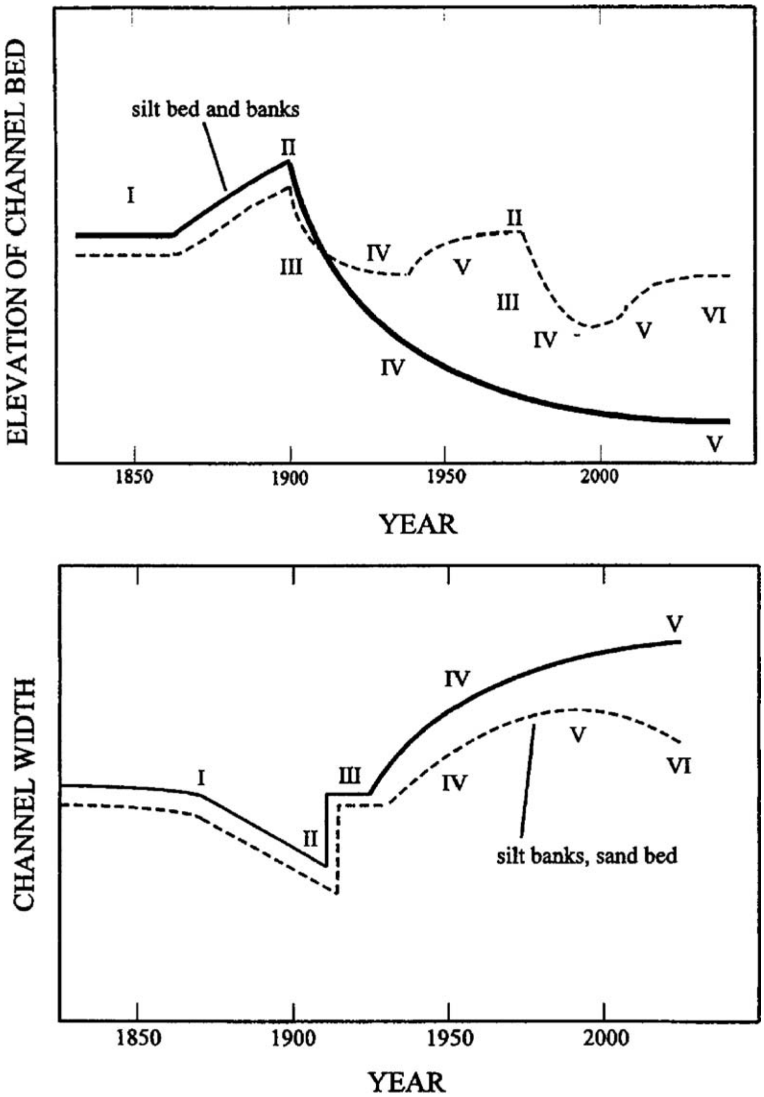

Fig. 11. Idealized representation of trends of channel adjustment since 1850 in the mid-continent of the United States for channelized silt-and sand-bedded streams (from Simon and Rinaldi, 2000). Refer to Fig. 7 for stages of evolution represented by Roman numerals.

different bed-material sediments for the period 1850–2000 (Simon and Rinaldi, 2000). Sand-bed streams filled with deposited sediments during the 1930s through the 1950s necessitating re-dredging and clearing and snagging of downstream reaches. This additional channel work rejuvenated trunk and tributary streams causing the sequence of channel evolution to begin again (Fig. 11).

The sequence of channel evolution is less complicated for the streams of the region that cut only into loess sediments. In these cases, deep incision along trunk and tributary streams resulted from the initial channel work near the turn of the 20th century. The incision rapidly created bank heights in excess of the critical strength of the material and caused a long period of bank instability and channel widening (Fig. 11). Without significant reductions in bank heights by aggradation, channel widening by mass-wasting processes will continue through the 21st century until such time as (1) bank angles are reduced by successive failures in the same location, and (2) the channel becomes so wide that the frequency of bank-toe removal by fluvial action is reduced considerably.

5.3. Case study: Arno River, Central Italy

During the centuries before 1845, the Arno River (Fig. 12) was a depositional system with growing alluvial plains and delta progradation into the Mediterranean Sea. This is referred to as the Aggradational Phase

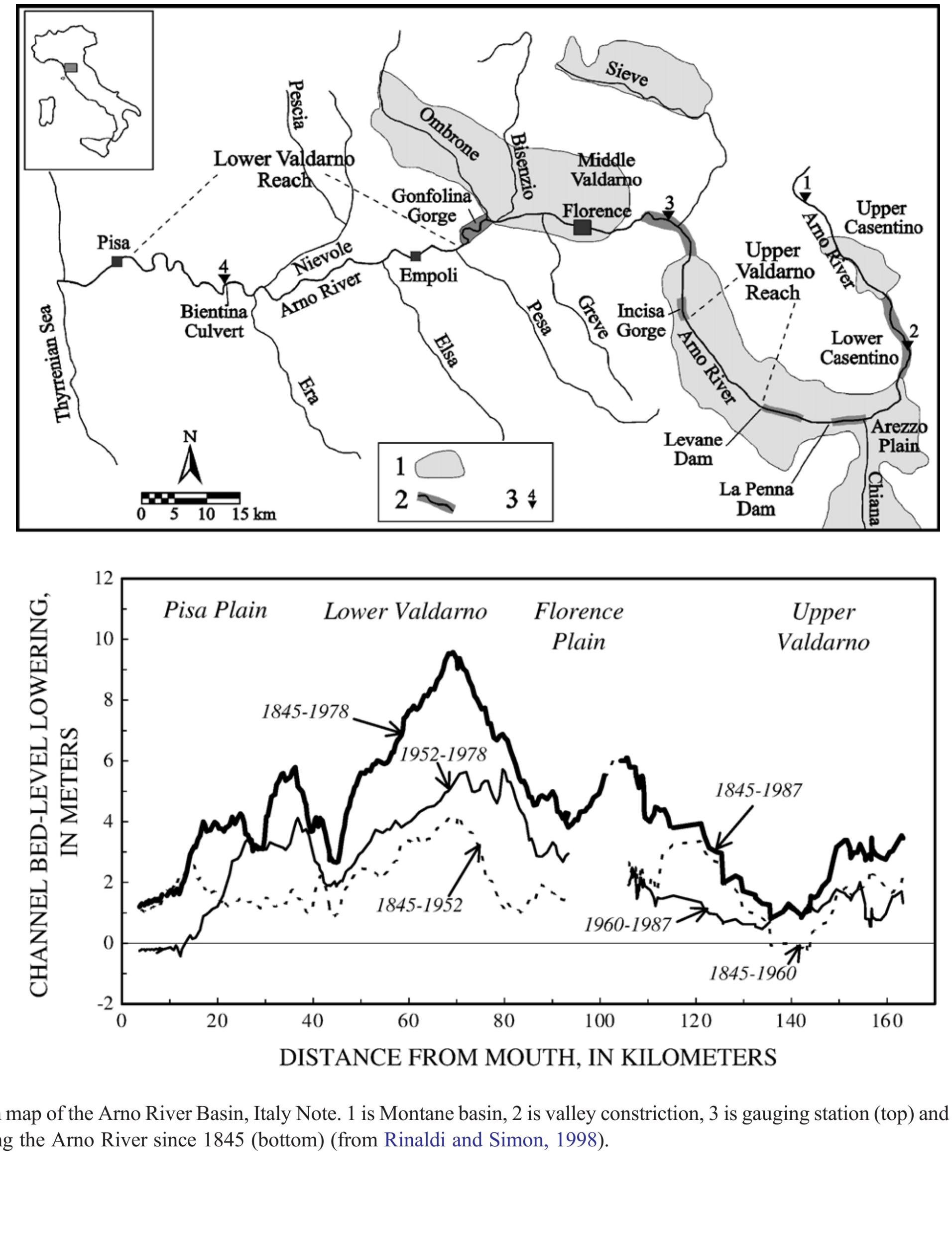

Fig. 12. Location map of the Arno River Basin, Italy Note. 1 is Montane basin, 2 is valley constriction, 3 is gauging station (top) and average lowering of bed-level along the Arno River since 1845 (bottom) (from Rinaldi and Simon, 1998).

(Billi et al., 1997). Although reliable data on bed-level adjustments prior to 1845 are not available, historical evidence (i.e. Giorgini, 1854) suggests that the channel bed was aggrading, or at least not degrading.

A series of land-management laws passed between 1877 and 1933 led to reforestation of large upland areas, causing sediment retention and a drastic reduction of sediment supplied to the fluvial system. Comparison of available topographic maps of the Arno River delta show that progradation was replaced by erosion after 1878 (Pranzini, 1983). Near the beginning of the 20th century, the channel bed started to degrade. During the last decades of the 20th century, other anthropogenic disturbances, primarily gravel mining and dam construction on the main stem, disrupted the balance between sediment supply and transport capacity, inducing severe degradation (Fig. 12). Trends of bed-level adjustments through time have been analyzed by Rinaldi and Simon (1998) for a large number of cross-sections in the two main alluvial reaches in the Upper and Lower Valdarno, where the river was free to adjust its morphology to imposed changes.

Application of Eq. (2) to describe bed-level adjustments resulting from the discontinuous disturbances showed more than one degradational phase (Fig. 13) and provided a general model of bed-level adjustment over the past 100 years for the principal alluvial reaches of the Arno River (Upper Valdarno and Lower Valdarno) (Rinaldi and Simon, 1998). From 1845 until 1900, the general trend of bed-level adjustment was probably mild aggradation. Any tendency for aggradation was probably balanced by the increased sediment-transport capacity because of re-dredging and narrowing of the channel in the years near the turn of the 20th century. Bed elevation was, therefore, assumed to be relatively constant between 1845 and the beginning of the degradation phase. The fitted curve for the first degradational phase (Phase I) suggests that lowering of the bed started at the turn of the 20th century. The at-a-site analysis (Fig. 13) shows the existence of two main degradational phases subsequent to the Aggradational Phase: first a minor one (Phase I) between the end of the 19th century and the first half of the 20th century, with bed lowering about 0.5–2 m; and a second one (Phase II) starting in the period 1945–1960, with 1–3 m of bed lowering in the Upper Valdarno and up to 8 m in the Lower Valdarno.

The first degradational phase is mainly the result of land use changes that caused a decrease in the sediment supplied to the fluvial system. The second degradational phase is mainly the result of two superimposed disturbances: intense in-stream gravel mining and the construction of two dams. These disturbances resulted in large imbalances between the transport capacity of the flow and the amount of bed sediment supplied from upstream, resulting in incision due to excess transport capacity, which caused a relative increase in bed-material transport, a decrease of channel gradient, and an associated reduction in sediment-transport capacity.

The Arno River has incised at varying magnitudes along its alluvial reaches over the past 150 years as a result of multiple changes in sediment supply at the watershed scale resulting from reforestation and dam construction, and more local changes in available stream power that resulted from channelization and gravel mining. Adjustments to channel width are of limited significance along the Arno River, predominantly because bank protection such as concrete linings, rip rap,

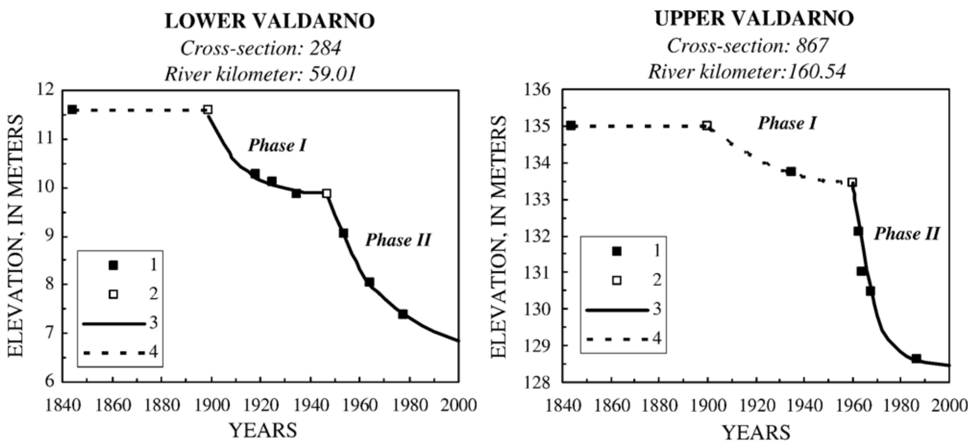

Fig. 13. Examples of fitting Eq. (2) to bed-level trends through time to identify two phases of degradation since 1845 (from Rinaldi and Simon, 1998). Note. 1 refers to surveyed data; 2 is assumed data; 3 is the fitted function; and 4 is the assumed trend.

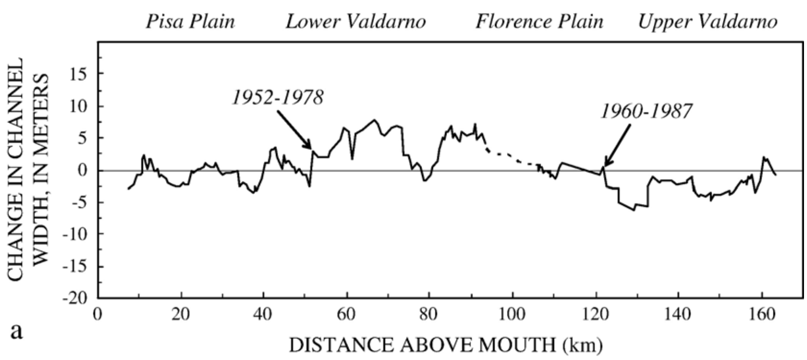

Fig. 14. Changes in channel width along alluvial reaches of the Arno River.

and gabions are common (Fig. 14). The absence of downstream aggradation on the Arno River that is described by Schumm et al. (1984) and Simon (1989) in other settings, on the Arno River, may be attributed to (1) the general lack of widening, (2) a limited amount of sediment supplied to downstream reaches because of the presence of the dams, and (3) because sediment mining carried out along the same downstream reaches drastically reduced the amount of sediment available for transport.

6. Stream power, flow energy and channel adjustment

General trends of changes in channel morphology because of channelization activities in the mid-continent of the United States and reduced sediment supply to the Arno River, Italy provide a semi-quantitative view of how different disturbances can cause similar types of adjustments (incision). Differences in boundary sediments, however, can cause differences in the relative magnitudes of vertical and lateral processes during adjustment. Still, the disturbances described above, thus, represent only several possible anthropogenic effects amongst a litany of changes that can be imposed on a fluvial system that result in incision, widening and enormous increases in sediment loads. Moreover, as has been noted previously, differences in boundary sediment and available stream power can drive aggradation rather than incision in some settings (Landwehr and Rhoads, 1993), even though the human impact (e.g. channelization) is identical in all other regards.

To analyze how an alluvial channel might adjust to an increase in stream power (Relation 1) it is useful to identify the component parts of stream power or energy and to track changes over the course of fluvial adjustment. Numerous researchers have shown that the response of an alluvial system to disturbance can be defined by non-linear decay functions that become asymptotic and reach minimum variance with time. Variables used include: entropy production (Karcz, 1980); channel gradient (Simon and Robbins, 1987); sediment discharge (Parker, 1977; Simon, 1999); stream power (Bull, 1979; Simon, 1992) relative degradation (Begin et al., 1981; Williams and Wolman, 1984); relative roughness (Davies and Sutherland, 1983; Simon and Thorne, 1996); and flow energy and the rate of energy dissipation ((Simon, 1992; Simon and Thorne, 1996; Simon and Darby, 1997; Simon, 1999). This concept is summarized in Fig. 15, which shows idealized adjustment trends for a site with excess energy or stream power. The curves represent trends in important controlling variables computed for a single discharge based on relations from the literature cited above for periods of 10–100 years. The upper part of the figure represents non-linear decreases in available force or energy or sediment load with increasing time after the disturbance, while the bottom part represents increases in roughness and resistance to entrainment. Actual relations show considerably more scatter about the

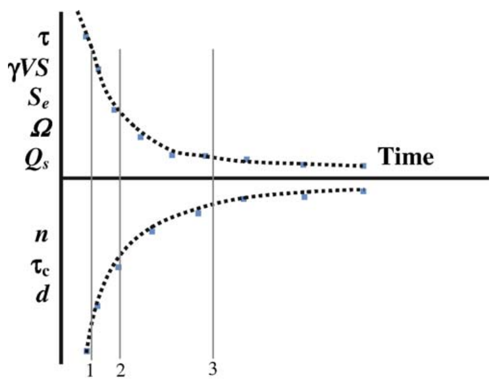

Fig. 15. Idealized representation of adjustment trends in a reach with excess flow energy. Note: τ is boundary shear stress; γVS=unit stream power; S_e is the energy slope; Ω is total stream power; Q_s is sediment load; n is Manning's roughness; τ_c is critical shear stress; and d is the characteristic diameter of bed sediment.

idealized trends as will be shown below. Many of the variable trends depicted in Fig. 15 could very well be opposite in reaches responding to an excess sediment supply as in downstream reaches of channelized systems.

Total mechanical energy per unit weight of fluid (H; head) is the sum of the gravitational potential head and the velocity head:

$$H = z + y + (\alpha v^2/2g) \tag{4}$$

where H=total mechanical energy per unit weight of fluid (m); z=the mean channel-bed elevation (m); α coefficient for non-uniform distribution of velocity; and g is acceleration of gravity (m/s^2).

$$h_f = [z_1 + y_1 + (\alpha_1 v_1^2/2g)] - [z_2 + y_2 + (\alpha_2 v_2^2/2g)] \tag{5}$$

where h_f is total head loss (m).

Flow energy (Eq. (4)) and rate of energy dissipation (expressed as head loss; Eq. (5)) or stream power (Eq. (3)) provide a framework to interpret the hierarchy of adjustment process in different morpho-climatic settings, as is shown below.

6.1. A naturally occurring upstream disturbance in an alpine environment

An example from the North Fork Toutle River, Washington (Fig. 16) shows data for two reaches adjusting following the eruption of Mount St. Helens and the associated burial of the drainage-network of the river to an average depth of 60–80 m (Simon, 1992, 1999). The net result of adjustment processes for both reaches over the ten-year period following the eruption is characterized by a minimization of: (1) the rate of energy dissipation; and (2) the ability of the river to transport bed-material sediment (expressed as average boundary shear stress; Fig. 16). Responding to the same disturbance (a massive increase in potential energy and sediment supply), the “Elk Rock Reach” predominantly reduced energy by degradation and widening, while further downstream the “Salmon B Reach” reduced energy predominantly by aggradation and widening. That both reaches reduced energy even though the Salmon B Reach was increasing bed elevation (potential energy) by aggradation, can be explained by the effects of channel widening. Widening reduces flow depth (pressure head) for a given flow, increases relative roughness and, therefore, also reduces flow velocity (kinetic energy). Widening in combination with degradation, as occurred in the Elk Rock Reach, represents the most efficient means of energy reduction, because each component of total mechanical energy is reduced (Simon, 1992). In these examples, similar unstable reaches, impacted by an identical disturbance, responded differently because of differences in the relative magnitude of the sediment supply from upstream compared to transporting capacity.

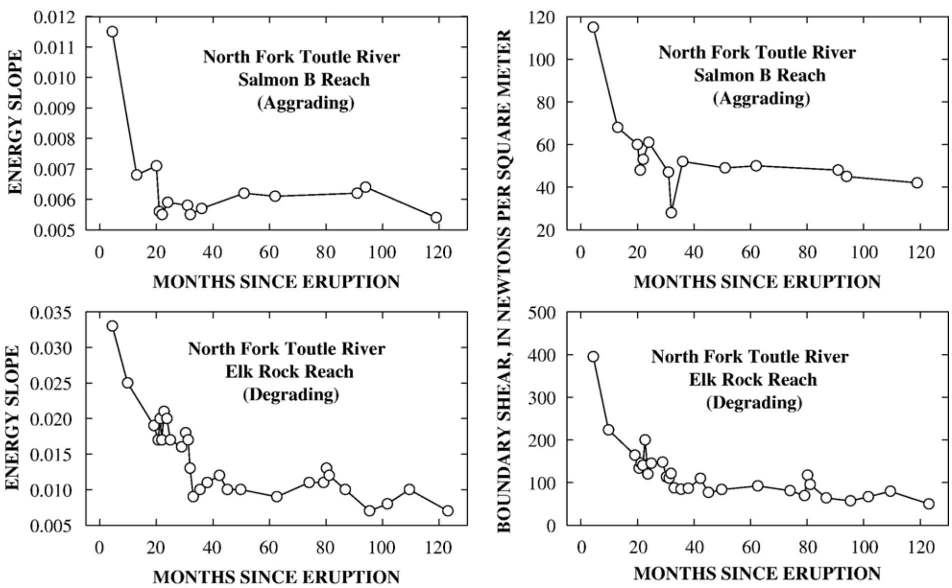

Fig. 16. Non-linear reductions in the rate of energy dissipation (expressed as energy slope) (left) and average boundary shear stress (right) for a constant discharge between 1980 and 1990 for two reaches along the North Fork Toutle River, Washington following the 1980 eruptions of Mount St Helens (modified from Simon (1992, 1999).

The non-linear, asymptotic nature of these relations for a given discharge is explained in terms of the magnitude of the difference between the available energy or stream power imposed by the post-disturbance stream channel, and the critical stream power. This imbalance is at a maximum immediately following a disturbance and results in a maximum rate of energy dissipation and morphologic change. In upstream reaches this occurs through changes in datum head (bed elevation), channel gradient, velocity head, hydraulic depth and roughness. Although adjustment is a continuous process acting over the range of flows, it is convenient for discussion to consider it as a series of discrete events. The initial maximum adjustment reduces excess energy or stream power by an amount proportional to the available energy and critical conditions for entrainment. With a diminished amount of excess energy or stream power available for the next event, smaller changes occur. If this process is repeated over a number of events of equal magnitude, each successive adjustment will be smaller, resulting in a non-linear asymptotic adjustment function.

The smooth, non-linear trends depicted in Figs. 15 and 16 do not imply that scatter or oscillations do not occur in response to subsequent flows. Detailed analysis of individual events in the Elk Rock Reach (Fig. 16) showed that deposition (as opposed to the general trend of degradation) occurred during low and moderate flows. This oscillatory phenomenon is explained by Simon (1992) in terms of reductions in specific energy for flows in the sub-critical and super-critical regimes. Rhoads (1990) has reported similar findings for a semi-arid river in terms of low flows having lower stream power per unit area and, therefore, being unable to transport all of the sediment delivered to the reach.

6.2. Comparison with a channelized system in a Coastal Plain environment

Channelization of the sand-bed streams in West Tennessee created upstream migrating knick zones that resulted in hundreds of kilometers of failed banks and millions of tonnes of sediment erosion (Simon, 1989b; Simon and Hupp, 1992). Though the Obion-Forked Deer River System of West Tennessee and the Toutle River System, Washington were drastically different, trends of vertical adjustment were almost identical (Fig. 3). Differences in the magnitude of specific adjustment processes are explained in terms of the resistance and character of the boundary sediments, with the West Tennessee streams having moderately cohesive, fine-grained banks.

Average rates of widening in the Toutle River system were 10–20 m/year compared to 0–3.5 m/year in West Tennessee. This is because the cohesive banks of the Obion River system were more effective at resisting mass failure in middle and upstream reaches, yet when eroded, the fine bank sediment was transported through the system and did not contribute to downstream aggradation. In contrast, coarse-grained bank sediments in the Toutle River system readily were eroded and provided an important source of hydraulically-controlled sediment for downstream aggradation.

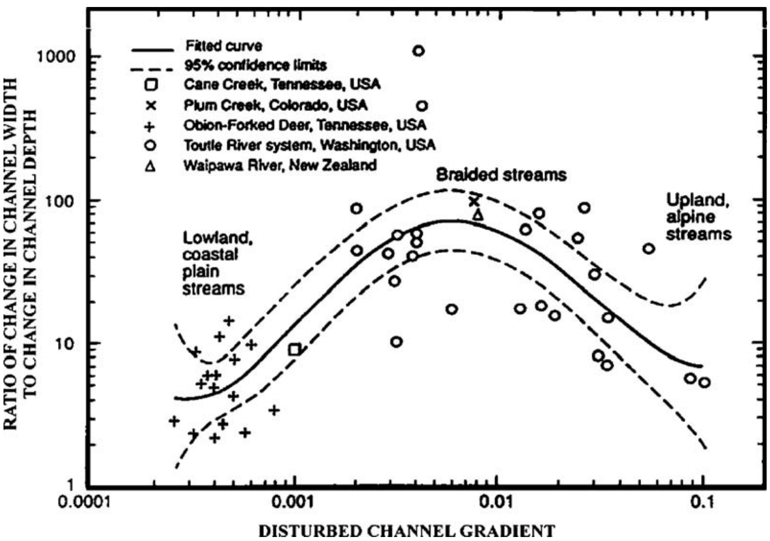

Fig. 17. Ratio of change in channel width to change in channel depth during adjustment for streams from different morpho-climatic settings.

Table 3
Boundary characteristics used for numerical simulations of a sand channel with initial slope of 0.005 m/m and width/depth ratio of 13.5 (modified from Simon and Darby, 1997)

Bank material	Bed d_{50} (mm)	Bank cohesion (kPa)	Friction angle (o)	Sand content (%)
Sand	1.0	4.0	32.5	100
Silt	1.0	7.5	32.5	20
Clay	1.0	40.0	32.5	10

Changes in channel width divided by changes in depth differed by an order of magnitude for the two systems, with means of 59 and 5.4 for the Toutle ($n=16$) and Obion-Forked Deer ($n=25$) systems, respectively. This again, reflects the greater resistance of the cohesive banks in West Tennessee and the importance of separating and accounting for differences between bed-and bank-material properties. When plotted against disturbed channel gradient, this index of channel change (Simon, 1992) provides a conceptual picture of the relative magnitudes of vertical and lateral adjustment following a disturbance resulting from excess flow energy in different fluvial environments (Fig. 17).

The above discussion is an example of how different disturbance events can lead to similar spatial and temporal trajectories of degradation, aggradation, and widening, although the varying magnitudes of response result in different channel morphologies. Although the two systems were exposed to physically different disturbances, both represent conditions of excess energy and stream power relative to sediment supply.

7. Simulation of the effect of bank materials on channel incision

A numerical model of bed deformation and channel widening was used (Darby, 1994; Darby et al., 1996) to simulate channel response to a reduction of upstream

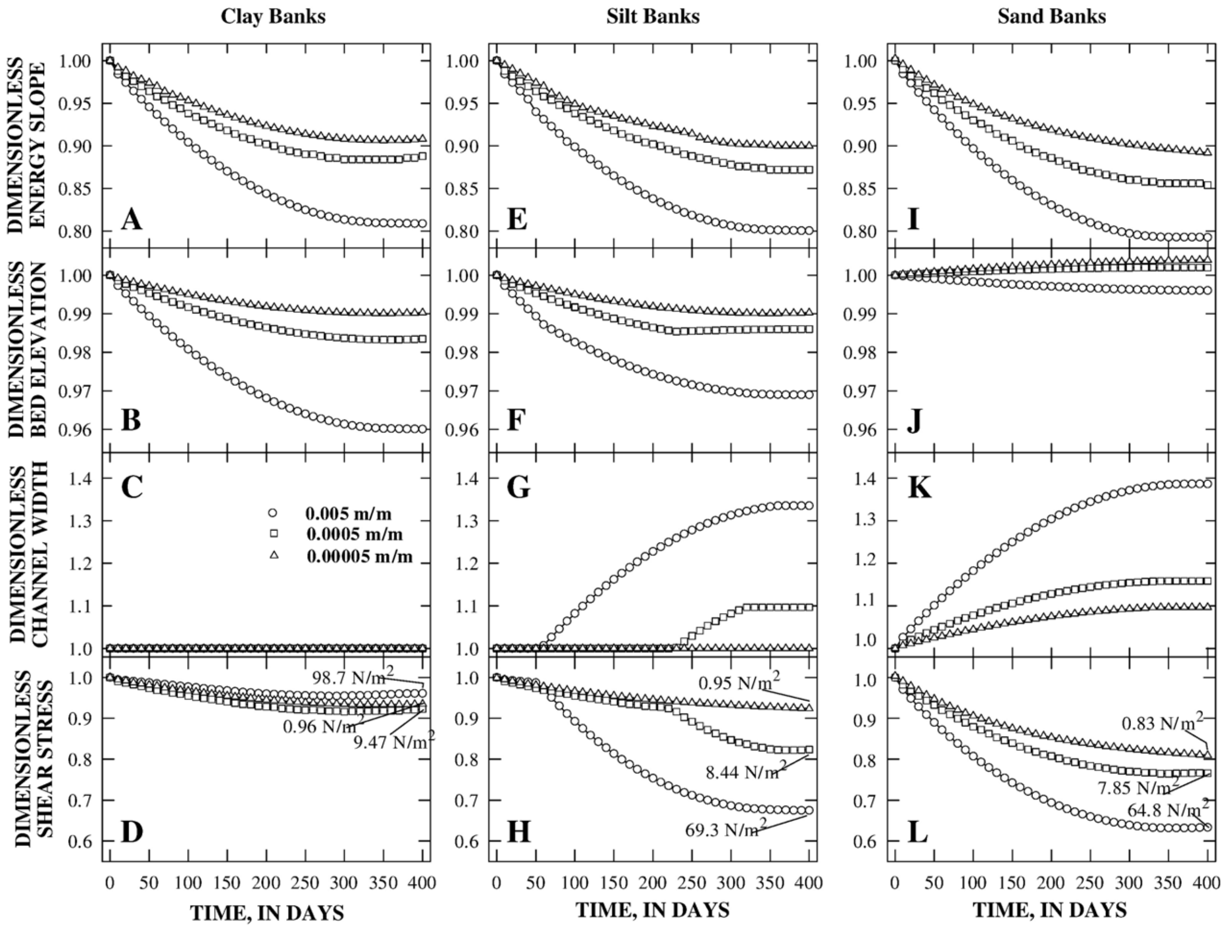

Fig. 18. Adjustment trends for simulated sand-bed channels with banks of varying cohesive strength (see Table 3). Note identical equilibrium values of dimensionless, energy dissipation rate (A, E, I) for a given channel gradient (from Simon and Darby, 1997).

Table 4
Summary of simulation results following disturbance of stable, "reference" C-5 channels with different bank materials (modified from Simon and Darby, 1997). W_f/D_f is the final, equilibrated width/depth ratio

Initial channel slope	0.005 m/m	0.001 m/m	0.0005 m/m
Clay-bank channel			
Degradation (m)	3.5	2.6	1.3
Widening (m)	0.0	0.0	0.0
W_f/D_f	5.6	6.7	9.0
Silt-bank channel			
Degradation (m)	2.7	1.8	1.1
Widening (m)	11.3	7.2	3.3
W_f/D_f	8.6	9.3	10.5
Sand-bank channel			
Degradation (m)	0.4	0.3	−0.2
Widening (m)	13.1	7.8	5.4
W_f/D_f	16.4	15.0	16.6

sediment supply (50% of transport capacity) for sand-, silt-, and clay-bank channels with an initial slope of 0.005 m/m (Simon and Darby, 1997). This scenario is similar to a real-world situation where the upstream sediment supply has been reduced by construction of a dam (Williams and Wolman, 1984) or upland re-forestation or other erosion-control measures have reduced delivery of coarse sediment (Rinaldi et al., 1997; Rinaldi and Simon, 1998). Characteristics of the boundary sediments are shown in Table 3, with the cohesion value for the clay-bank channel set such that the banks would remain stable throughout the simulations.

Because disturbances to the three channels represented an equal, but excessive amount of flow energy relative to upstream sediment supply (Relation 1), adjustments were manifest by almost identical non-linear, asymptotic reductions in the rate of energy dissipation (to 0.80 of initial, expressed as energy slope; H_f) as the channels adjusted to new equilibrium morphologies (Fig. 18). Yet, although the reduction over time in energy dissipation was similar among the model runs, these adjustments occurred by different processes operating at different rates and magnitudes, and resulted in different, stable channel morphologies (Table 4). For the run with a slope of 0.005 m/m, the essentially fixed banks of the clay-bank channel experienced 3.5 m of incision, compared to 2.7 m for the silt-bank channel and 0.4 m for the sand-bank channel. In contrast, channel widening by mass failure did not occur in the clay-bank channel, yet was 11.3 m and 13.1 m for the silt-and sand-bank channels, respectively.

Thus, although each of the channels was initially stable, differences in bank resistance and composition resulted in different adjustment scenarios and different stable morphologies (Table 4; Fig. 18). Limited incision occurred in the sand-bank channel because bank instability (widening) at the start of the simulation provided reductions in hydraulic depth and plentiful sand to the channel. Aggradation was the dominant bed process for the sand-bank channel having an initial slope of 0.0005 m/m (Table 4). Finally, after adjustment from an initial slope of 0.005 m/m, equilibrium width/depth ratios ranged from 5.6 to 16.4, an order of magnitude difference.

8. Discussion and conclusions

Channel incision is part of denudation, drainage-network development, and landscape evolution. Rejuvenation of fluvial networks by channel incision often leads to further network development and an increase in drainage density as gullies migrate into previously non-incised surfaces.

Large, anthropogenic disturbances, similar to large or catastrophic "natural" events, greatly compress time scales for incision and related processes by creating enormous imbalances between upstream sediment delivery and available transporting power. Channel incision and slope reductions that might occur over millennia under "natural" conditions of change may take place in 10–100 years following drastic fluvial disruptions. This was certainly the case on the debris-avalanche surface in the valley of the North Fork Toutle River at Mount St. Helens post-1980 where development of a new fluvial network and asymptotic reductions in flow energy, shear stress and stream power took place in about 10 years (Fig. 16). Incision, as a response to channelization in sand-bed streams in Iowa and West Tennessee (Figs. 1 and 2) occurred over

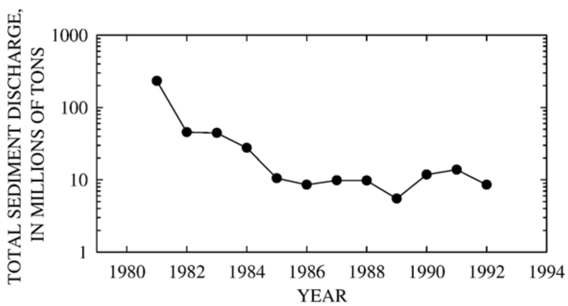

Fig. 19. Sediment discharge from the Toutle River System, Washington following the 1980 eruptions of Mount St. Helens.

similar time scales. Longer periods of downcutting occurred in those streams such as West Tarkio Creek (Fig. 10), where a limited supply of hydraulically-controlled sediment was available in the bed and banks that could offset the increased transport capacity and provide material for downstream aggradation. These empirical field observations are supported by numerical simulations of sand-bedded channels with differing bank materials (Fig. 18) and by theoretical relations of time-dependent adjustments in flow energy, shear stress and stream power (Fig. 15).

The non-linear asymptotic nature of fluvial adjustment to incision caused by channelization or other causes is borne out in similar temporal trends of sediment loads from disturbed systems. Experimental work by Parker (1977) and Begin et al. (1981) show non-linear adjustment trends in sediment yield that include oscillations of decreasing amplitude. Measured data trends from Toutle River System are similar (Fig. 19). The sediments emanating from incised channels can represent a large proportion of the total sediment yield from a landscape, with erosion from the channel banks generally the dominant source (Table 1). Contributions of sediment from incised stream channels can reach tens of millions of tonnes per year. Sediment derived as an incision product is stored along stream courses in bars, floodplains, terraces and deltas and, therefore, plays a significant role in determining downstream landscape features and physical and aquatic impacts.

Incised river channels are ubiquitous features of disturbed landscapes. Whether the disturbances result from natural causes or are the result of human activities, and whether they operate at very slow rates over long periods of time (thousands of years) or are catastrophic and instantaneous, channel incision occurs because of an imbalance between sediment supply and sediment transporting power. Disturbances that effect available force, stream power or flow energy, or change erosional resistance such that an excess of flow energy occurs can result in incision. Channel incision, therefore, can be considered a quintessential feature of dis-equilibrated fluvial systems.

References

Ashley, G.H., 1910. Drainage problems in Tennessee. Tennessee State Geological Survey Bulletin, vol. 3-A, pp. 1–15.

Barnard, R.S., Melhorn, W.N., 1982. Morphologic and morphometric response to channelization: the case history of Big Pine Creek Ditch, Benton County, Indiana. In: Craig, R.G., Craft, J.L. (Eds.), Applied Geomorphology, Proc., 11th Binghamton Geomorphology Symposium, pp. 224–239.

Begin, Z.B., Meyer, D.F., Schumm, S.A., 1981. Development of longitudinal profiles of alluvial channels in response to base-level lowering. Earth Surface Processes and Landforms 6, 49–68.

Billi, P., Rinaldi, M., Simon, A., 1997. Disturbance and adjustment of the Arno River, Central Italy I: historical perspective, the last 2,000 years. In: Wang, S.S.Y., Langendoen, E.J., Shields Jr., F.D. (Eds.), Management of Landscapes Disturbed by Channel Incision. University of Mississippi, Oxford, pp. 256–261.

Brice, J.C., 1966. Erosion and deposition in the loess mantled Great Plains, Medicine Creek Drainage Basin, Nebraska. U.S. Geological Survey Professional Paper, vol. 352-H, pp. 255–339.

Brookes, A., 1987. The distribution and management of channelized streams in Denmark. Regulated Rivers 1, 3–16.

Brookes, A., 1988. Channelized Rivers: Perspectives for Environmental Management. John Wiley and Sons, Chichester. 326 pp.

Bryan, B.A., Simon, A., Outlaw, G.S., Thomas, Randy, 1995. Methodology for assessing channel conditions at bridges in Tennessee related to scour critical conditions. U.S. Geological Survey Water-Resources Investigations Report, vol. 94-4229. 54 pp.

Bull, W.B., 1979. Threshold of critical power in streams. Geological Society of America Bulletin 90, 453–464.

Daniels, R.B., 1960. Entrenchment of the Willow Drainage Ditch, Harrison County, Iowa. American Journal of Science 258, 161–176.

Darby, S.E., 1994, A physically-based numerical model of river channel widening: PhD thesis, University of Nottingham, UK, 276 pp.

Darby, S.E., Thorne, C.R., Simon, A., 1996. Numerical simulation of widening and bed deformation of straight sand-bed rivers II: model evaluation. Journal of Hydraulic Engineering 122, 194–202.

Davies, T.R.H., Sutherland, A.J., 1983. Extremal hypotheses for river behavior. Water Resources Research 19 (1), 141–148.

Elliott, J.G., 1979, Evolution of large arroyos, the Rio Puerco of New Mexico. Colorado State University, Fort Collins, Colorado, Master of Science thesis, 106 pp.

Emerson, J.W., 1971. Channelization: a case study. Science 172, 325–326.

Giorgini, C., 1854. Sui fiumi nei tronchi sassosi e sull'Arno nel piano di Firenze. Tipografia delle Murate, Firenze. 230 pp.

Hadish, G.A., 1994. Stream Stabilization in Western Iowa, Iowa DOT HR-352. Golden Hills Resource Conservation and Development, Oakland, Iowa. 198 pp.

Hidinger, L.L., Morgan, A.E., 1912. Drainage problems of the Wolf, Hatchie, and South Fork Forked Deer Rivers, in West Tennessee. The Resources of Tennessee, Tennessee Geological Survey, vol. 2 (6), pp. 231–249.

Ireland, H.A., Sharpe, C.F.S., Eargle, D.H., 1939. Principles of gully erosion in the Piedmont of South Carolina. U.S. Department of Agriculture Technical Bulletin, vol. 633. 142 pp.

Karcz, I., 1980. Thermodynamic approach to geomorphic thresholds. In: Coates, D.R., Vitek, J.D. (Eds.), Thresholds in Geomorphology. George Allen & Unwin, London, pp. 209–226.

Keller, E.A., 1972. Development of alluvial stream channels: a five-stage model. Geological Society of America Bulletin 83, 1531–1536.

Landwehr, K., Rhoads, B.L., 1993. Depositional response of a headwater stream to channelization, East Central Illinois, USA. River Research and Applications 19, 77–100.

Lane, E.W., 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings of American Society of Civil Engineers 81 (795), 1–17.

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. W.H. Freeman and Co., San Francisco. 522 pp.

Little, W.C., Murphey, J.B., 1981. Evaluation of streambank erosion control demonstration projects in the bluffline streams of northwest Mississippi. Appendix A, Stream Stability Report to Vicksburg

District, U.S. Army Corps of Engineers, AD-A101-386. National Technical Information Service. 342 pp.
Lohnes, R.A., Klaiber, F.W., Dougal, M.D., 1980. Alternate methods of stabilizing degrading stream channels in western Iowa. Iowa DOT HR-208, Department of Civil Engineering, Engineering Research Institute. Iowa State University, Ames, Iowa. 132 pp.
Luttenegger, A.J., 1987. In situ shear strength of friable loess. In: Pesci, M. (Ed.), Loess and Environment, Catena Supplement, vol. 9, pp. 27–34.
Mackin, J.H., 1948. Concept of a graded river. Geological Society of America Bulletin 59, 463–511.
Moore, C.T., 1917. Drainage districts in southeastern Nebraska. In: Barbour, E.H. (Ed.), Miscellaneous Papers, Nebraska Geological Survey, vol. 7, pp. 125–164. part 17.
Morgan, A.E., McCrory, S.H., 1910. Drainage of the lands overflowed by the North and Middle Forks of the Forked Deer River, and the Rutherford Fork Obion River in Gibson County, Tennessee. Tennessee State Geological Survey Bulletin 3-B, 17–43.
Parker, R.S., 1977. Experimental study of drainage system evolution and its hydrologic implications. Hydrology Papers, No. 90. Colorado State University, Denver. 58 pp.
Parker, G., Andres, D., 1976. Detrimental effects of river channelization. Conference on Rivers, vol. 76. ASCE, Ft. Collins, Colorado, pp. 1248–1266.
Piest, R.F., Beer, C.E., Spomer, R.G., 1976. Entrenchment of drainage systems in western Iowa and northwestern Missouri. Proc., Third Federal Inter-agency Sedimentation Conference, pp. 5-48–5-60.
Piest, R.F., Elliott, L.S., Spomer, R.G., 1977. Erosion of the Tarkio drainage system, 1845–1976. Transactions of American Society of Agricultural Engineers 20, 485–488.
Pollen, N., Simon, A., Klimetz, L., Klimetz, D., 2006. Stability analysis of the Buttahatchee River Basin, Mississippi and Alabama. USDA_ARS National Sedimentation Laboratory technical Report. 135 pp.
Pranzini, E. 1983. Studi di geomorfologia costiera. IX- L'erosione del delta dell'Arno (Studies of coastal geomorphology IX- Erosion of the Arno River delta), Quaderni del Museo di Storia Naturale di Livorno 4, 7–18.
Rinaldi, M., Simon, A., Billi, P., 1997. Disturbance and adjustment of the Arno River, Central Italy II: quantitative analysis of the last 150 years. In: Wang, S.S.Y., Langendoen, E.J., Shields Jr., F.D. (Eds.), Management of Landscapes Disturbed by Channel Incision. University of Mississippi, Oxford, pp. 256–261.
Rhoads, B., 1990. The impact of channelization on the geomorphic stability of an arid-region river. National Geographic Research 6, 157–177.
Rinaldi, M., Simon, A., 1998. Bed-level adjustments of the Arno River, central Italy. Geomorphology 22, 57–71.
Robbins, C.H., Simon, A., 1983. Man-induced channel adjustment in Tennessee streams. U.S. Geological Survey Water-Resources Investigations Report, vol. 82-4098. 129 pp.
Ruhe, R.V., Daniels, R.B., 1965. Landscape erosion-geologic and historic. Journal of Soil and Water Conservation 20, 52–57.
Schumm, S.A., 1999. Causes and controls of channel incision. In: Darby, S.E., Simon, A. (Eds.), Incised River Channels, Processes, Forms, Engineering and Management. John Wiley & Sons, Chichester, pp. 19–33.
Schumm, S.A., Hadley, R.F., 1957. Arroyos and the semiarid cycle of erosion. American Journal of Science 225, 161–174.
Schumm, S.A., Harvey, M.D., Watson, C.C., 1984. Incised Channels, Morphology, Dynamics and Control, Water Resources Publications, Littleton, Colorado. 200 pp.
Simon, A., 1999. Channel and drainage basin response of the Toutle River System in the aftermath of the 1980 eruption of Mount St. Helens, Washington, U.S. Geological Survey Open-File Report, 96-633. 130 pp.
Simon, A., 1994. Gradation processes and channel evolution in modified West Tennessee streams: process, response, and form. U.S. Geological Survey Professional Paper, vol. 1470. 84 pp.
Simon, A., 1992. Energy, time, and channel evolution in catastrophically disturbed fluvial systems. In: Phillips, J.D., Renwick, W.H. (Eds.), Geomorphic Systems, Geomorphology, vol. 5, pp. 345–372.
Simon, A., 1989a. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14, 11–26.
Simon, A., 1989b. The discharge of sediment in channelized alluvial streams. Water Resources Bulletin 25 (6), 1177–1188.
Simon, A., Bingner, R.L., Langendoen, E.J., Alonso, C.V., 2002. Actual and reference sediment yields for the James Creek Watershed, Mississippi. National Sedimentation Laboratory Research Report, vol. 31. 185 pp.
Simon, A., Darby, S.E., 1997. Process-form interactions in unstable sand-bed river channels: a numerical modeling approach. Geomorphology 21, 85–106.
Simon, A., Dickerson, W., Heins, 2004b. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: transport conditions at the bankfull and effective discharge? Geomorphology 58, 243–262.
Simon, A., Hupp, C.R., 1992. Geomorphic and vegetative recovery processes along modified stream channels of West Tennessee. U.S. Geological Survey Open-File Report, vol. 91-502. 142 pp.
Simon, A., Hupp, C.R., 1986. Channel evolution in modified Tennessee channels. Proceedings, Fourth Federal Interagency Sedimentation Conference, Las Vegas, March 24–27, 1986, vol. 2, pp. 5–71–5–82.
Simon, A., Langendoen, E., Bingner, R., Wells, R.R., Yuan, Y., Alonso, C., 2004a. Suspended-sediment transport and bed-material characteristics of Shades Creek, Alabama and Ecoregion 67: developing water-quality criteria for suspended and bed-material sediment. National Sedimentation Laboratory Technical Report, vol. 43. 150 pp.
Simon, A., Rinaldi, M., 2000. Channel instability in the loess area of the midwestern United States. Journal of the American Water Resources Association 36 (1), 133–150.
Simon, A., Thomas, R.E., 2002. Processes and forms of an unstable alluvial stream with resistant, cohesive streambeds. Earth Surface Processes and Landforms 27, 699–718.
Simon, A., Thorne, C.R., 1996. Channel adjustment of an unstable coarse-grained stream: opposing trends of boundary and critical shear stress and the applicability of extremal hypotheses. Earth Surface Processes and Landforms 21, 155–180.
Speer, P.R., Perry, W.J., McCabe, J.A., Lara, O.G., et al., 1965. Low-flow characteristics of streams in the Mississippi Embayment in Tennessee, Kentucky, and Illinois, with a section on Quality of water, by H.G. Jeffery: U.S. Geological Survey Professional Paper 448-H. 36 pp.
Thorne, C.R., 1999. Bank processes and channel evolution in the incised rivers of north-central Mississippi. In: Darby, S.E., Simon, A. (Eds.), Processes, Forms, Engineering and Management. John Wiley & Sons, Chichester, pp. 97–122.
U.S. Army Corps of Engineers, 1907, Index map of the South Fork of Forked Deer River, Tennessee from Jackson to the mouth. Nashville, Tennessee State Archives, scale 1:48,000, 1 sheet.

Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper, vol. 1286. 83 pp.

Wilson, K.V., 1979. Changes in channel characteristics, 1938−1974, of the Homochitto River and tributaries, Mississippi, U.S. Geological Survey Open-File Report, 76-554. 18 pp.

Wilson, K.V., Turnipseed, D.P., 1994. Geomorphic response to channel modifications of Skuna River at the State Highway 9 crossing at Bruce, Calhoun County, Mississippi. U.S. Geological Survey Water-Resources Investigations Report, vol. 94-4000. 43 pp.